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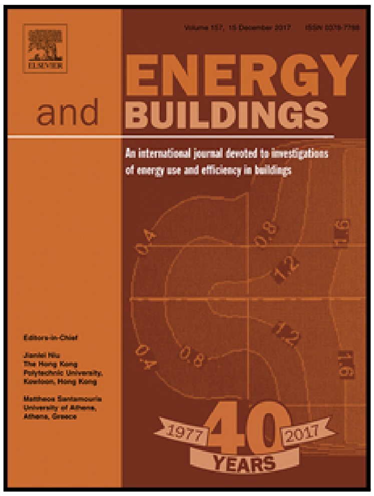


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Highlight

- Five types of well-developed $VO_2$-based thermochromic glazing were selected, and studied under five climatic conditions in China
- The effects of thermochromic glazing on daylight availability and energy consumption were detailed discussed, and analysed
- The thermochromic glazing can provide significant energy saving for office with large glazing area, meanwhile reduce excessive daylight when compared with a traditional double glazing

# Evaluation of the thermal and optical performance of Thermochromic Windows for Office Buildings in China

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**Abstract**

Thermochromic (TC) windows were developed as a passive building component to improve indoor comfort and building energy conservation in place of traditional clear glazing systems. Thermochromic materials have the ability to regulate daylight and solar heat gains through windows stimulated by heat. This means that when the temperature of a thermochromic window becomes higher than its transition temperature, less solar radiation, primarily in the near infrared, will be admitted inside the building, reducing over-heating on hot days. The aim of this research is to explore the potential of thermochromic glazing under various climatic conditions by modelling the energy and daylight performance of a typical office room with five different thermochromic glazing types ( with varying transition temperatures ranging from 20°C to 41.3°C and solar transmittances ranging from 0.412 to 0.690) simulated under five climatic conditions in China, representative of different climate zones. A comprehensive analysis was conducted, including a study of the thermal and optical behaviours of the selected thermochromic glazed windows; energy use for heating, cooling and artificial lighting of the selected office; and effects of window-to-wall ratios on office performance under the selected climatic conditions. The objectives are: to thoroughly understand the characteristics of the selected types of thermochromic glazing, to find the appropriate window-to-wall ratio for the thermochromic windows, and to investigate the suitability of thermochromic glazing for particular climatic conditions to realise which could achieve energy conservation and desired daylighting simultaneously. The results showed the following: 1) Low transition temperature (i.e. 20$^{o}$C) is not essential for building energy conservation, larger modulation of solar transmittance is more desirable for most of the climatic conditions. 2) Higher solar absorptance could increase thermochromic layer temperatures, improving glazing tinting capability, but it may increase window heat gains in the form of secondary heat gains and further induce cooling energy consumption on hot days. 3) All the studied thermochromic windows led to building energy savings (up to 19.9%) and better daylighting performance (i.e. increase of the desired range of illumination, $UDI_{500\text{-}2000lux}$, is up to 15.52%) when compared with traditional clear double glazing. 4) Under climates such as Harbin and Beijing with more cold days, limited types of thermochromic glazing could achieve both energy conservation and desired daylighting under a particular window size, while almost all types of thermochromic glazing are suitable to be used in climates with more hot days.

**Keywords**

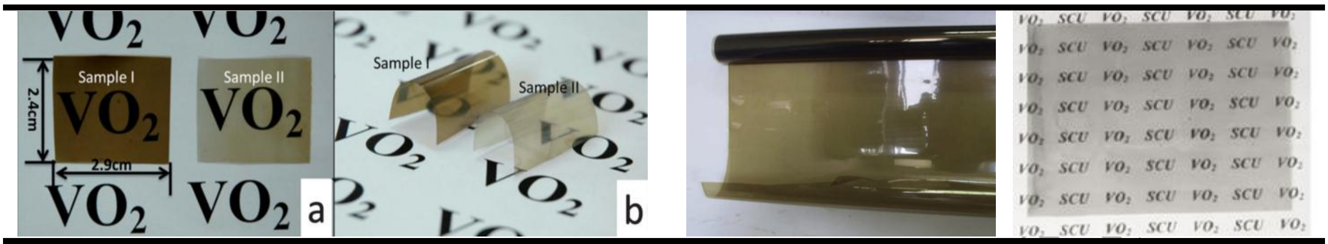
Thermochromic glazing; Building simulation; Useful Daylight Illuminance; Solar Heat Gain Coefficient (SHGC).

## 1. Introduction

Over the past decades, there has been an increase in public awareness with regards to the importance of energy saving and quality of indoor environment on occupant health and comfort. Energy consumption from buildings accounts for a significant proportion (approximately 40%) of the world's primary energy consumption. In developing countries such as China, the proportion is predicted to increase from 28% to 35% by 2020 [1]. Greenhouse gas emissions caused by building energy consumption is one of the main causes of global warming [2]. Therefore, energy conservation has become a focus of energy policies and decision making for architectural design [3, 4]. In a typical domestic residence, heating, cooling, lighting and hot water contribute to approximately 60% of total energy consumption. Meanwhile, a commercial building consumes less heating, but more energy on cooling and lighting by around 15% [5]. Window systems play a unique role as the transparent component within a building which provides daylight, views to the external environment and fresh air to the occupants. Notwithstanding, they are considered to be thermally weak, as around 60% of energy loss can be caused by conduction, convection, and radiation through windows [6]. Therefore, designing and selecting an optimal window system is an essential strategy for maximising the benefits of occupant comfort and building energy efficiency [7]. Many elements determine the selection of windows, such as the building type (i.e. domestic / non-domestic), climates and so forth. Window types available to choose from include low-cost single gazing, highly insulated double/triple glazing, windows with different solar control functions (low-e glazing, high reflectance metallic glazing), and innovative smart windows that dynamically control the transmitted solar radiation [8-18].

Recently, smart windows have increasingly been considered to be an efficient technology for improving building performance. Smart windows can be composed of chromogenic materials, able to sense and respond to external stimulus and control solar energy passage. Based on their stimulus, chromogenic materials can be categorised as electrochromic (stimuli is electricity), photochromics (stimuli is light), gasochromics (stimuli is gas) and thermochromic (stimuli is heat). Amongst them, thermochromic smart windows have a relatively simple structure and the feature of being able to reversibly change their optical properties by directly responding to temperature. Vanadium dioxide ($VO_2$), first reported in 1959, is one of the most promising materials for this purpose [19]. $VO_2$ has a transition temperature (Tt) of 68℃, which means that when the temperature rises above this, a fully reversible metallic to semiconductor phase transition (MST) takes place, associated with a change in optical properties in the near-infrared region (NIR, the cause of heat) of solar radiation [19]. In past decades, lower transition temperature, high visible transmittance and a significantly large modulation of NIR transmittance after transition were considered to be most desirable for window application. Therefore, a large number of $VO_2$-based materials with more desirable properties were studied and produced through a variety of chemical fabrication methods, such as Tungsten doped (W-doped) $VO_2$ films [20], Mg-doped $VO_2$ films [21], $VO_2$ films with low transition temperature [22], and $VO_2$

nanoparticles [23]. Figure 1 illustrates a few TC film samples, the pure $VO_2$ and $VO_2$-based nanoparticle films appear to have a yellow/brown visual appearance (Figure 1 (a) (b)), while the W-doped $VO_2$ film is a grey-blue (Figure 1(c)).




**(a) $VO_2$ @ $SiO_2$ nanoparticles [24]** (b) Pure $VO_2$ **[25]** (c) 1.5%W-doped $VO_2$ **[26]**

**Figure 1: Samples of $VO_2$ based thermochromic films**

To realise the application of the thermochromic (TC) materials in a building as an energy efficient window component, studies of their energy performance have been conducted. Saeli, Ye, Long, Hoffmann, and Warwick [27-30] have investigated the building energy saving potential of some TC materials developed in the lab though building energy simulation. When comparing $VO_2$ based TC windows with low-e and tinted absorbing glass respectively, Saeli *et al.* found that TC windows can reduce more building energy consumption, and this energy saving was more significant in warmer climates rather than in cooler ones [27, 28]. Ye *et al.* [25] investigated the performance of typical $VO_2$ glazing applied in an office room setting through building energy simulation. It was found that 10.2-19.9% cumulative cooling load could be reduced in comparison to standard clear glazing [25]. In addition, two experiments have been undertaken to test the performance of $VO_2$-based TC windows. One of the experiments was conducted by Gao *et al.* [31] using a scaled model where the effect of the TC window on the internal space temperature was monitored; it was observed that the studied TC glazing could reduce the indoor temperature by 9°C. The other experiment was carried out by Ye and Long [25, 31, 32] as a full-scale model to validate the building simulation and test daylight availability. The measurements showed that ~80% illuminance was blocked.

With the purpose of understanding the optical properties (i.e. solar transmittance, absorptance, reflectance, and long-wave emissivity) of TC windows that may affect their energy performance, some hypothetical studies were conducted. Ye *et al.* [33] found that, in comparison with solar transmittance, lower long-wave emissivity can result in more energy saving; and a high absorptivity after transition for TC windows may result in higher energy consumption. Ye and Long [34, 35] developed a series of indexes to estimate whether a TC material could be categorised as energy efficient, such as Energy Consumption Index (ECI), Energy Saving Equivalent (ESE), Energy Saving Index (ESI) and Smart Index (SI). Their studies further indicated that a $VO_2$ material, which has a large decrease of solar transmittance and a lower increase of absorptivity after the transition, has larger energy saving potential [34, 35]. Warwick *et al.* [30] studied the relationship between transition temperature and theoretical hysteresis gradients and found that TC glazing with the lowest transition temperature and sharpest hysteresis gradient could reduce 51% of the energy demand in comparison to standard clear glazing. Moreover, the hysteresis gradient was significant in enhancing energy saving [30]. Hoffmann studied a series of hypothetical TC windows with different transition temperatures to find the optimised thermochromic characteristics. This study quantified window solar heat gains, heating, cooling, and lighting energy use, all of which would be influenced by these hypothetical TC windows. Different window sizes and orientations under various climatic conditions were also explored, and both energy consumption and visual comfort were evaluated. It was found that the TC windows reduced the number of hours that occupant glare and discomfort occurred whilst 13.7%-16.7% energy consumption could be reduced with optimised orientation and large-area windows in hot climates[29].

A large proportion of previous studies focus on material development of $VO_2$-based TC windows [31, 36, 37], while only a limited number of simulations have been carried out to understand their effects on the energy performance and visual comfort of a building whilst also incorporating the lab development of TC materials [25, 27, 28, 32, 34]. This research aims to explore the thermal and visual performance influenced by current lab-developed TC materials working under different climatic conditions in China. It also, therefore, explores TC performance in an increased level of detail relating to the following research questions:

1) Which climatic zones are most suitable for $VO_2$ based TC windows?

2) Will TC materials with lower transition temperature close to room temperature (20-25°C) result in larger energy reduction than those with a higher transition temperature?

3) Will TC materials with a large increase in absorptance after transition be more energy efficient?

4) Will TC materials reduce illuminance levels within indoor spaces, while simultaneously decreasing the risk of glare in comparison with traditional clear glazing?

5) What is the best lab developed TC window for various climatic zones throughout China?

## 2. Methodology

This study was carried out by modelling a typical office installed with different types of windows and investigating their performance under five different climates within China. EnergyPlus was used to conduct a series of computation, aiming to obtain significant values including tinted hours, solar heat gain coefficient (SHGC), energy consumption and useful daylighting illuminance (UDI).

### 2.1. Climates

This simulation was calculated by averaging one hour time steps for a year using the IWEC (International Weather for Energy Calculation) weather file for five different climates in China representative of the following five major climatic zones [38]: Harbin as a severe cold zone (SCZ), Beijing as a cold zone (CZ), Hangzhou as a hot summer and cold winter zone (HSCWZ), Kunming as a temperate zone (TZ), and Guangzhou as a hot summer and warm winter zone (HSWWZ). Detailed location and climatic properties for the zones, such as temperature and solar radiation, are specified in Table 1 [39]. The average monthly temperature for each zone is shown in Figure 2, where it can be seen that Harbin has the lowest average winter temperature of -20°C in January and a relatively warm summer of 22°C, where space heating is dominant. Guangzhou has a monthly average temperature ranging from 15-30 °C throughout the year, where cooling is primarily required. For Beijing and Hangzhou, both heating and cooling are required, however, due to the fact that Kunming has a temperate climate, there are times when neither heating nor cooling is required. In terms of incident solar radiation, summer months have a higher average than that of winter months. Additionally, it is necessary to notice that with decreasing latitude of the cities, solar altitude (i.e. the angle of the sun relative to the Earth's horizon) increases correspondingly, which might affect the daylighting accessibility into the building via the windows.

**Table 1 climatic properties of five representative cities in different climatic zones in China[39]**

| | Location | | Temperature (°C) | | Solar radiation (W/m$^2$) | | Climatic zones |
|---|---|---|---|---|---|---|---|
| | Latitude | Longitude | Max. | Min. | Max. | Min. | |
| **Harbin** | 45.7°N | 126.7°E | 29 | -28.4 | 186.8 | 112.4 | SCZ |
| **Beijing** | 39.8°N | 116.5°E | 37.1 | -10.1 | 156.4 | 93.2 | CZ |
| **Hangzhou** | 30.2°N | 120.2°E | 35.6 | -1.8 | 114.3 | 61.3 | HSCWZ |
| **Kunming** | 25.0°N | 102.7°E | 27.4 | -1.3 | 160.5 | 55.0 | TZ |
| **Guangzhou** | 23.1°N | 113.3°E | 35 | 6.6 | 142.4 | 38.6 | HSWWZ |

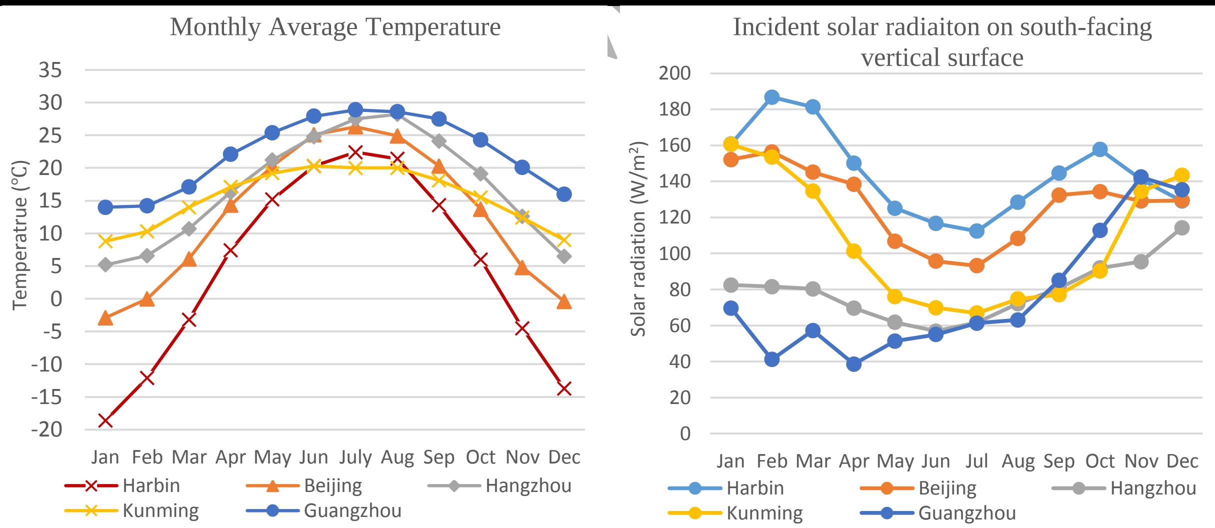



**Figure 2: Monthly average temperatures (left) and solar radiation incident on the vertical surface of the south wall (right) in five selected cities respectively.**

## 2.2. Simulation set up

### 2.2.1. Model set up

The energyplus software was developed by Lawrence Berkeley National Laboratory (LBNL) and the US Department of Energy, which has been widely used to simulate and evaluate the performance of buildings [40]. It has also been used for studies of TC windows and other advanced glazing systems [27, 29, 30], and has been proven to be one of a highly appropriate building simulation program in the field. It was, therefore, chosen to study the thermal and daylight performance of the selected TC windows.

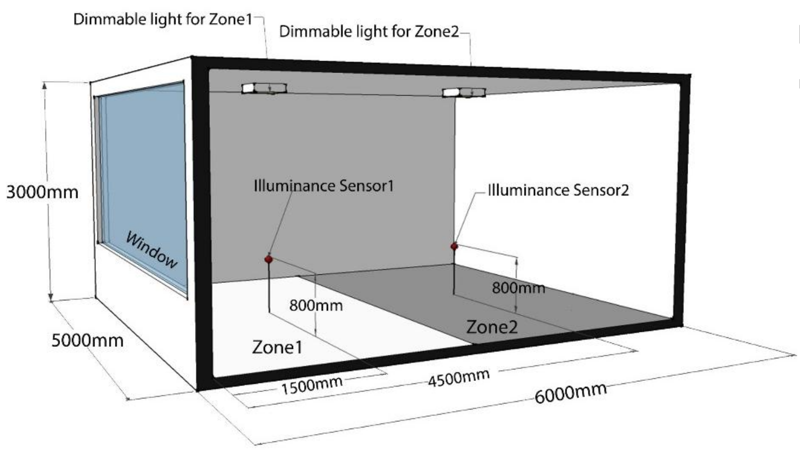



**Figure 3: Typical office room with a 4.5m×2m window (located over 60% of the wall)**

A typical office room with external dimensions of 6m×5m×3m (length × width × height) was constructed in EnergyPlus for this study. The room was modelled to be a mid-floor office within a multi-story building, representative of a generic south facing office in the northern hemisphere. Therefore, only the south wall of the room was assumed to be exposed to outdoor conditions, and other room surfaces were assumed to be buffered by uniformly conditioned adjacent rooms, yielding no heat transfer. According to the energy efficiency building standards in China [41], thermal properties of building envelopes have different requirements under different climate zones. It is difficult to reflect this climatic consideration within a single model,therefore the modelling options chosen were those which satisfied the majority of thermal requirements applicable. For the settings of the building envelopes, the U-value of the external wall was set to be 0.43W/m$^2$k, the ceiling 1.21 W/m$^2$k and the floor 1.13 W/m$^2$k. Five types of TC windows, as well as the reference clear window, were all based on double-glazed systems (U-value 2.7W/m$^2$k) without shading devices installed. As Figure 3 illustrates, the artificial lighting was controlled by a two-zoned automatic dimmer for supplying natural daylighting, to meet the illuminance target level of 500lux at working plane, with a distance of 800mm from the floor [42]. The two illuminance sensors were designated in the centres of two zones respectively to monitor the horizontal daylight illuminance and control dimming: Sensor 1 is in zone 1 close to the window (1.5 meters away), and Sensor 2 is in zone 2 further away from the window (4.5 meters away). Internal loads and schedules were set up as follows: An occupant density is 18.6m$^2$/per person and primarily occupied the room between 9 am to 5 pm on weekdays. Equipment loads were 13W/m$^2$, and lighting loads were 11W/m$^2$. To diminish the influence of HVAC systems and highlight the building performance affected by the different types of TC windows, indoor temperature was controlled to a constant 21ºC, appropriate for both winter and summer in most non-domestic building applications [43]. Working hours range from 9 am to 5 pm during weekdays throughout of the year. In order to quantify the performance of TC windows influenced by window size, the Window-to-Wall Ratio (WWR, defined as net glazing area/ total wall area where a window is located) was varied from 0.1 to 1 in intervals of 0.1, i.e. the first simulation model has WWR of 0.1, the second one has WWR of 0.2, and so on.

### 2.2.2. Materials

Five types of TC glazing were selected, and Table 2 shows properties of an external layer of double glazing: WV_t20 is a W-doped $VO_2$ film with the characteristic of the lower transition temperature of approximately 20ºC [22]. WV_t40 is a $VO_2$ film fabricated by co-sputtering coated with W-doped with a transition temperature of 40ºC [44]. $VO_2$_t38 is glazing with $VO_2$ film fabricated by hybrid aerosol assisted and atmospheric pressure chemical vapour deposition (AA/AP CVD) with the reaction of a surfactant called TOAB, its transition temperature is 38.5ºC [27]. $VO_2$_t41is another pure $VO_2$ film manufactured by State Key Laboratory of High-Performance Ceramics and Superfine Microstructure, Shanghai Institute of Ceramics (SIC), Chinese Academy of Sciences (CAS) with a transition temperature of 41.3 ºC [25]. $NVO_2$_t40 is a $VO_2$ nanoparticle coated glazing, a novel $VO_2$-based material with a hypothetical transition temperature of 40ºC [23]. Based on their characteristics, the five types of TC glazing were categorised into three different groups:

1) High visual transmittance of approximately 0.6 at cold state ($VO_2$_t38 and $NVO_2$_t40).
2) Similar average solar and visual transmittance of approximately 0.45, but different transition temperature varying from 20°C to 40°C (WV_t20, WV_t40, and TC_$VO_2$).
3) Same transition temperature (40°C) and a similar reduction of solar transmittance after the transition of approximately 12% (WV_t40 and $NVO_2$_t40).

**Table 2: Properties of selected $VO_2$-based TC glazing**

| Properties | WV_t20 | | WV_t40 | | $VO_2$_t38 | |
|---|---|---|---|---|---|---|
| | S-state | M-state | S-state | M-state | S-state | M-state |
| **Transition temperature ($T_t$)** | 20ºC | | 40ºC | | 38.5ºC | |
| **Colour** | Green/Blue | | Green/Blue | | Yellow/Brown | |
| **Solar transmittance ($T_{sol}$)** | 0.44 | 0.39 | 0.412 | 0.288 | 0.460 | 0.380 |
| **Visible transmittance ($T_{vis}$)** | 0.39 | 0.39 | 0.394 | 0.346 | 0.610 | 0.510 |
| **Solar reflectance (ρ)** | 0.18 | 0.20 | 0.067 | 0.082 | 0.230 | 0.210 |
| **Solar absorptance (α)** | 0.38 | 0.42 | 0.521 | 0.630 | 0.310 | 0.410 |
| **Long wave emissivity (e)** | 0.84 | 0.84 | 0.840 | 0.840 | 0.830 | 0.790 |

| Properties | $VO_2$_t41 | | $NVO_2$_t40 | | Clear Glazing | |
|---|---|---|---|---|---|---|
| | S-state | M-state | S-state | M-state | --- | --- |
| **Transition temperature ($T_t$)** | 41.3ºC | | 40ºC | | --- | |
| **Colour** | Yellow/Brown | | Yellow/Brown | | Nature | |
| **Solar transmittance ($T_{sol}$)** | 0.440 | 0.355 | 0.69 | 0.57 | 0.78 | |
| **Visible transmittance ($T_{vis}$)** | 0.435 | 0.421 | 0.63 | 0.60 | 0.88 | |
| **Solar reflectance (ρ)** | 0.078 | 0.055 | 0.05 | 0.06 | 0.08 | |
| **Solar absorptance (α)** | 0.482 | 0.590 | 0.26 | 0.37 | 0.14 | |
| **Long wave emissivity (e)** | 0.880 | 0.880 | 0.84 | 0.84 | 0.84 | |

***S-state is the semiconductor state at a lower temperature than transition temperature, also named 'clear-state.'**
***M-state is the metallic state at a higher temperature than transition temperature, also named 'tinted-state.'**

Some assumptions were made to facilitate analysis and comparison: 1) Based on the report of the performance of these selected TC glazing the transition temperature range was assumed to be 8°C uniformly for each material, and there is no thermal hysteresis during the process of temperature increasing and decreasing [30]. 2) The TC material used in glazing $NVO_2$_t40 was assumed to have a transition temperature of 40$^o$C. This is due to the fact that the real transition temperature is around 60$^o$C, which is too high to achieve thermochromic transition practically under most of the climatic conditions, and 40$^o$C is a transition temperature with the potential to be achieved in terms of TC material fabrication [25, 27]. 3) Some missing data, such as long wave emissivity, was assumed to be the same as that of clear glazing (0.840), based on existing data ranging from 0.79 to 0.88 [25, 27, 29, 34, 35, 45].

## 2.3. Evaluation criteria

In order to understand the performance of thermochromic windows, specific evaluation criteria were applied for their analysis, including tinted hours, solar heat gain/loss, SHGC, heating/cooling load and UDI. These particular criteria are explained as follows:

**Tinted hours**: the number of hours when partially and fully tinted states occur for TC windows [27, 29]. According to the TC layer temperatures, three states were defined: Clear, partially tinted, and fully tinted. As aforementioned, the transition is a gradual process, and the transition temperature range is 8$^{o}$C for each material, which means that transition is continuous within the 8$^{o}$C around its transition temperature. For example, in terms of a TC glazing with a transition temperature of 40$^{o}$C, transition occurs with the temperature rising above 36$^{o}$C. When TC layer temperatures are between 36–44$^{o}$C, the state is categorised as partially tinted; when the temperature is over 44$^{o}$C, the state is categorised as fully tinted.

**SHGC:** The solar heat gain coefficient (SHGC) is the fraction of incident solar radiation admitted through a window, i.e. the ratio of window heat gains to incident solar radiation on the window surface. Window heat gains are made up of two main parts: 1) Solar radiation directly transmitted through the window; 2) Solar radiation absorbed and subsequently released inwards, known as secondary heat gains and expressed as a number between 0 and 1; The lower a window's SHGC, the less solar heat is transmitted into the room.

**UDI:** Useful Daylight Illuminance (UDI), is the fraction of time when indoor horizontal daylight illuminance at a given point falls into one of the given illuminance ranges (bins), which were defined by splitting the analysed period into a lower and upper illuminance limit. According to published findings on occupant preferences and behaviors, the rationale for the UDI range limits is summarised as the following [46]: 1) UDI within illuminance range lower than 500lux ($UDI_{<500lux}$), insufficient to be the sole source of illumination or contribute to artificial lighting significantly, or effective as the sole source of illumination, artificial lighting is required; 2) UDI within illuminance ranging across 500-2000lux ($UDI_{500-2000lux}$), desirable or at least tolerable, no artificial lighting is required; 3) UDI falling into illuminance range higher than 2000lux ($UDI_{>2000lux}$), likely to produce visual or thermal discomfort, shading may be required.

**WWR for energy saving (ES) and balanced illuminance (BI):** These evaluation criteria are used to analyze how window sizes influence energy saving and illuminance levels.

In terms of ES, this can be defined as the range of WWR values when TC windows can provide energy saving compared with the reference (DG) applied in the studied office room. When WWR falls in the range of ES, TC windows can be energy saving. Otherwise, they are more energy-consuming than the reference clear double glazing.

BI is the value of WWR when the desired daylight hour of sensor 1 and sensor 2 within the $UDI_{500-200lux}$ bin equate to one another. It is a balance point to get overall improved daylighting distribution in the office.

## 3. Results and Discussion

Energy consumption (i.e. heating, cooling and artificial lighting consumption) and daylight performance (i.e. UDI) of a typical office room with TC windows applied were investigated under five different climatic conditions. In addition, the effect of transition temperatures and optical properties of the $VO_2$-based thermochromic materials on the performance of TC windows, such as tinted hours, solar heat gains and SHGC have also been investigated. From the perspective of building design, the window size is another crucial element that affects both energy and daylight performance. The criterion for identifying the optimised TC window size was based on achieving a balance between daylight availability and energy-saving potential.

### 3.1 The characterisations of the selected thermochromic glazing

The temperature of the thermochromic glazing correlates with the optical and thermal properties of the thermochromic glazing (e.g. absorptance, solar transmittance modulation, reflectance, and transition temperature) as well as ambient conditions (e.g. outdoor and indoor ambient temperature and incident solar radiation intensity). Therefore, the combination of these effects on window optical and thermal behaviours was investigated, and their impact on the window heat gain and SHGC also discussed. In addition, the characterisation of selected glazing was investigated under the climatic condition in Beijing. As it has a hot summer and cold winter, Beijing is suitable to be a representative climatic condition to observe the various environmental impacts on the selected types of TC glazing.

#### 3.1.1. TC layer temperatures

##### 3.1.1.1 Tinted hours affected by material properties

The state of the TC window (clear or tinted) determines the amount of solar irradiance entering the room. If a thermochromic window is in a partially or fully tinted state, it results in less transmittance through the window, therefore less solar irradiance entering the room, useful in reducing summer cooling load. Figure 4 shows the partially tinted and fully tinted hours of five different types of TC glazing under Beijing's climate. Cooling period is from May to October and heating period ranges from November to April under the assumed HVAC operation condition that the thermostat temperature is fixed at 21 °C during occupied hours throughout the year, to fix the effect of indoor ambient temperature on thermochromic window temperature. The number of annual accumulated working hours is 2024. The number of tinted hours for WV_t20 is significantly higher than the other four types of TC glazing, which is 80.0% of the occupied hours throughout the year (Figure 4). This is mainly due to the transition temperature of 20°C for WV_t20, which is significantly lower than other types and relatively easy to be achieved under most of the climatic conditions. However, more tinted hours do not reflect higher energy efficiency or better daylight distribution. This is because an ideal thermochromic window is expected to spend the most hours during the cooling demand period in its tinted state, to block extra solar heat gains transmitted into the room during the cooling season. On the other hand, It is expected to admit more solar heat gains for passive heating during the heating season. For WV_t20, 38.6% of the tinted hours occur during the heating period, which may lead to more heating energy consumption to supplement the passive heating. WV_t40, $VO_2$_t38, $VO_2$_t41 and $NVO_2$_t40 have annual tinted hours of 39.4%, 20.6%, 29.8%, and 16.4% respectively. Although the annual total tinted hours of $VO_2$_t38 and $NVO_2$_t40 are less than the others, their tinted hours mainly occurred in the cooling period, i.e. 88.5% for $VO_2$_t38, and 89.7% for $NVO_2$_t40. The distribution of tinted hours is mostly approaching the ideal TC windows.

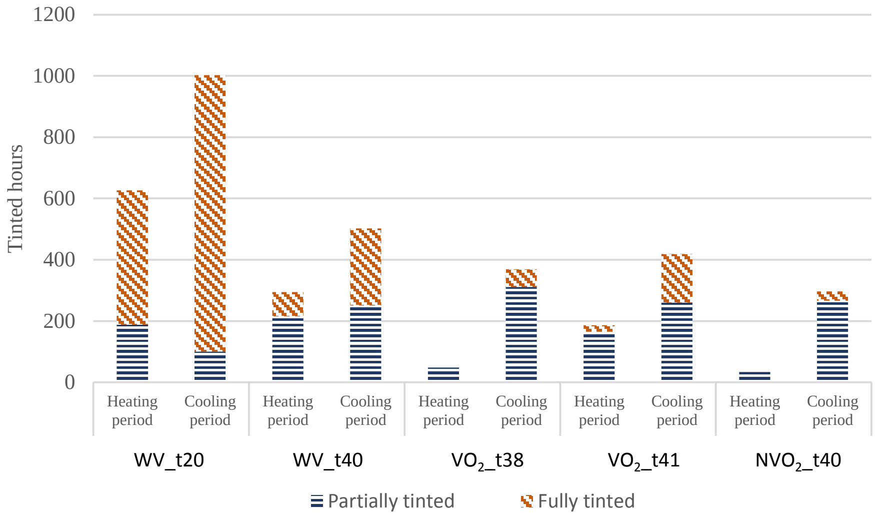



**Figure 4: Accumulated fully tinted and partially tinted hours of heating/cooling period respectively in Beijing**

Tinted hours are affected by transition temperature, solar absorptance, incident solar radiation intensities, ambient temperature and some convection effects. A higher solar absorptance improves the capability of the TC glazing to absorb solar irradiance, therefore increasing the window temperature. This may increase the probability of TC glazing to reach its transition temperature, whereby more tinted hours could be attained. On the other hand, a lower solar absorptance would inhibit the increase of window temperature, thus resulting in fewer occurrences of tinted hours.

Figure 5 presents the tinted state of all studied TC types affected by their transition temperature and solar absorptance in the cooling season. As can be seen, WV_t40, $VO_2$_t38, $VO_2$_t41, and $NVO_2$_t40 have similar transition temperatures ranging from 38.5 to 41.3°C. However, WV_t40 and $VO_2$_t41 have higher absorptance (i.e. 0.52-0.63 for WV_t40, 0.48-0.59 for $NVO_2$_t40), thus more tinted hours can be achieved than with $VO_2$_t38 and $NVO_2$_t40.

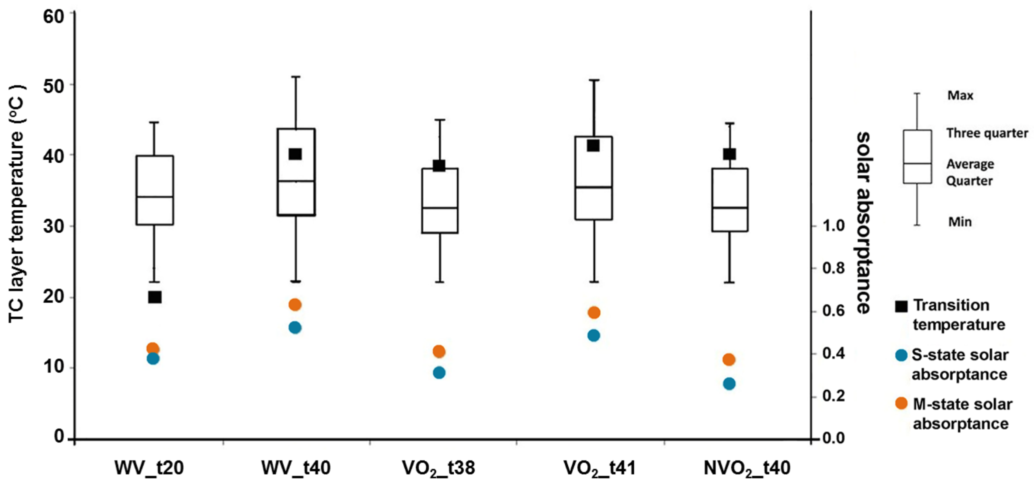
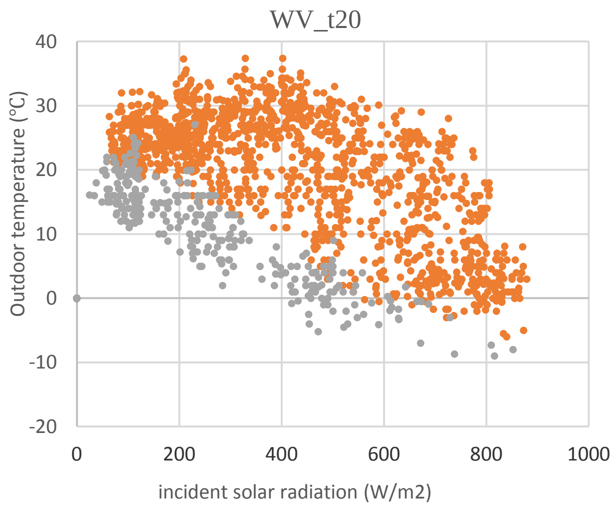


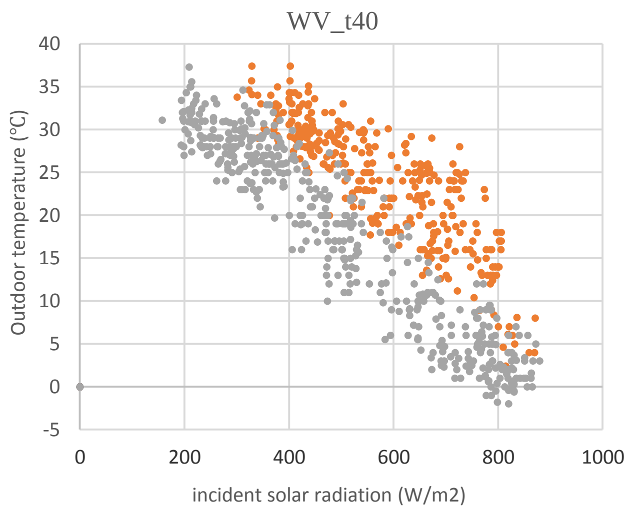

**Figure 5: TC layer temperature of five TC glazing Beijing during July working hours 9 am to 5 pm with a 21°C internal temperature controlled by HVAC.**

3.1.1.2 Tinted hours affected by ambient conditions

Based on the properties of different thermochromic materials, the studied TC windows can give a different response to the ambient conditions where they are applied. This means that ambient conditions also influence the performance of thermochromic behaviours. With a constant indoor temperature of 21°C, Figure 6 illustrates the hourly outdoor temperature and incident solar radiation output for the annual working hours when TC glazing is partially or fully tinted. Each point represents an outdoor temperature and corresponding incident solar radiation value. Consistent with tendency illustrated in Figure 4, WV_t20 has the highest tinted hours amongst the five types of TC glazing and most of the hours the glazing is in a fully tinted state. Most cases of tinting occur when the outdoor temperature is above the lower limit of the transition temperature range (i.e. 16°C).

However, there are occurrences of TC transition to tinted states when the outdoor temperatures are well below the transition temperature range, due to high levels of incident solar radiation. As can be seen, when the outdoor temperature ranges from 0-10°C, there are tinted hours which occur with incident solar radiation levels between 400 and 900W/m$^2$. It is indicated that the WV_t20 could also have a thermochromic transition on cold, sunny winter days with WV_t40and $VO_2$_t41 following similar tendencies. The TC transition occurs when the incident solar radiation levels range from 200 to 900 W/m$^2$, while the outdoor temperature is between 0-35°C. $VO_2$_t38 and $NVO_2$_t40 are another similar group with relatively low tinted hours and rare full tinted coverage. The main incident solar radiation and outdoor temperature for transition occurrences are 200-800 W/m$^2$ and 15-35 °C. Since the four types of TC glazing all have relatively high transition temperatures (around 40°C), and the outdoor temperatures of Beijing are predominantly below the transition temperatures, TC transition only occurs when the incident solar radiation levels are sufficient enough to raise the glazing temperature above the transition temperature. As was shown in section 3.1.1.1, a lower solar absorptance of TC glazing restricts the increase of their temperatures. Thus $VO_2$_t38 and $NVO_2$_t40 with absorptance ranging across 0.31-0.41 and 0.26-0.37 respectively, are more appropriate for application under a warmer climatic condition with higher solar radiation.



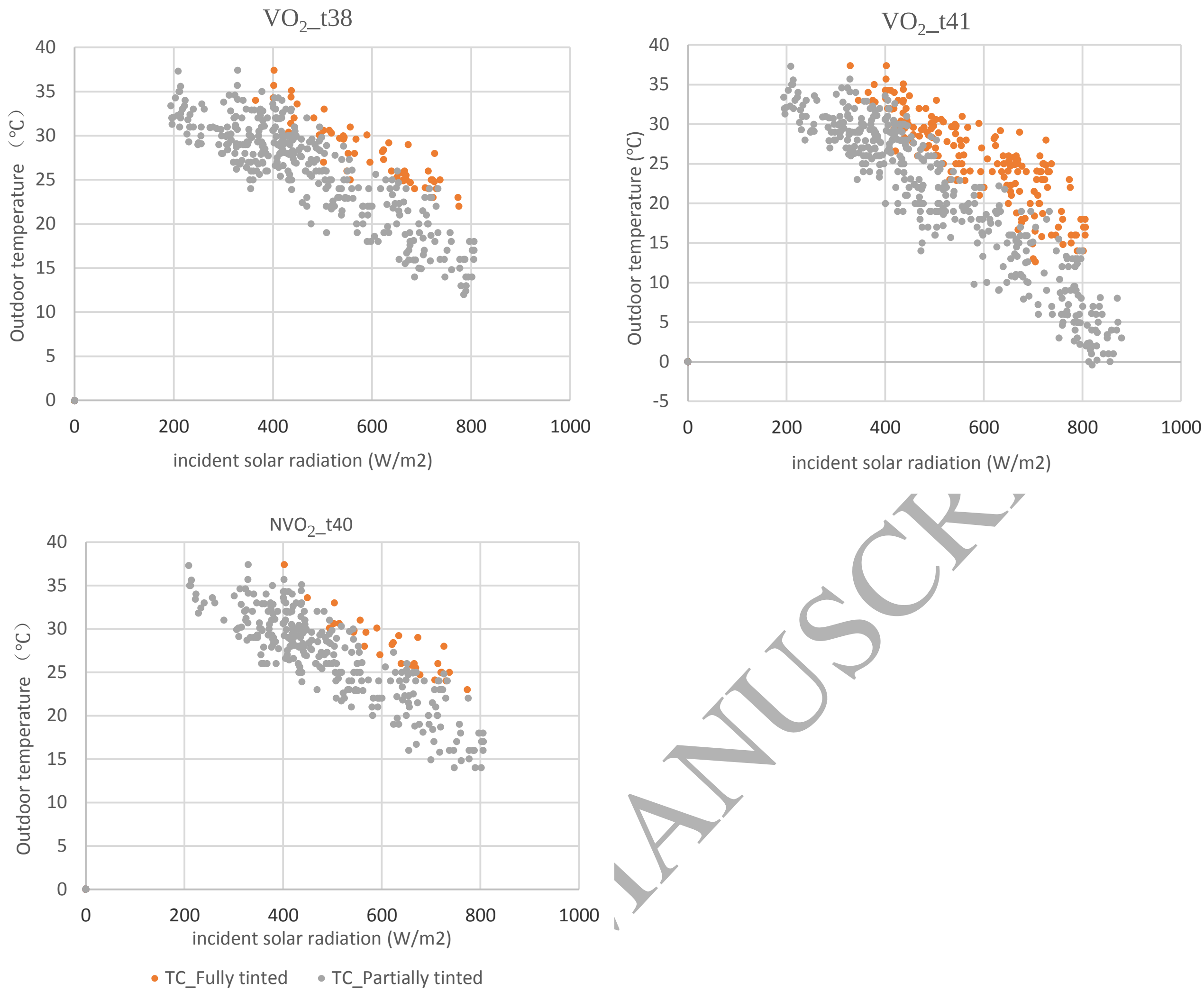



**Figure 6: The effects of outdoor incident solar radiation and outdoor ambient temperature on TC window states under Beijing's climate.The red dots show the hours when the window was fully tinted, and the grey dots show the hours when the window was partially tinted out of a total of 2024 working hours**

### 3.1.2. Window heat gains

Figure 7 shows the hourly window heat gain and incident solar radiation of standard double glazing (DG) and TC windows during occupancy hours throughout the year, also under the climatic conditions of Beijing. Each point represents solar heat gain by the window and its corresponding incident solar radiation. Blue points depict standard double glazing, and red points depict TC windows. The SHGC of each TC glazing is illustrated as the slope (k), which is obtained by dividing the value of window heat gain (y-axis) over the incident solar radiation (x-axis).

From the perspective of graphical analysis, the blue points' (DG) distribution is more concentrated than that of the red ones (TC). Therefore, the SHGC of the DG can be represented by a single slope using linear regression. The SHGC of TC windows was defined by two slopes, which present the minimum and maximum values of SHGC respectively. As can be seen in Figure 7, normal double glazing has a constant SHGC of 0.65, which is higher than that of all studied TC windows. WV_t40 represents the largest variation of SHGC, where the slope change is 0.134, ranging from 0.467 (K1) to 0.333 (K2) and $VO_2$_t41 has a slope variation of 0.108. Both WV_t40 and $VO_2$_t41 have relatively large variations of SHGC during the year, which means that they are potentially able to have increased thermochromic performance. Figure 8 shows the slopes changing with different states of TC windows in detail. Taking WV_t40 working in the hottest month of Beijing as an example, it is seen that the slope is declining from 0.433 to 0.383 with the sequence of clear, partially tinted, and fully tinted window results. This results in a decrease of transferring incident solar radiation to window heat gains. Additionally, fully tinted hours are concentrated in the region with high incident solar radiation (i.e. >120 $W/m^2$) and the corresponding lower SHGC could reduce cooling requirements. WV_t20 shows a modest change of SHGC ranging from 0.483 to 0.375, due to its restricted 5% solar transmittance change from 0.44 to 0.39. $VO_2$_t38 and $NVO_2$_t40 have relatively large solar transmittance changes, i.e. 8% and 12% respectively, however, they did not show the expected variation of SHGCs, the consequence of their lower tinted hours, as aforementioned. Moreover, $NVO_2$_t40 has an SHGC close to traditional double glazing, which varies from 0.625 to 0.516. This indicates that $NVO_2$_t40 transfers the largest proportion of solar radiation to window heat gains amongst all the studied TC windows. Overall, the TCs follow a similar trend of SHGC variation, with minute differences which correspond to the change of solar transmittance of each TC glazing shown in Table 1.

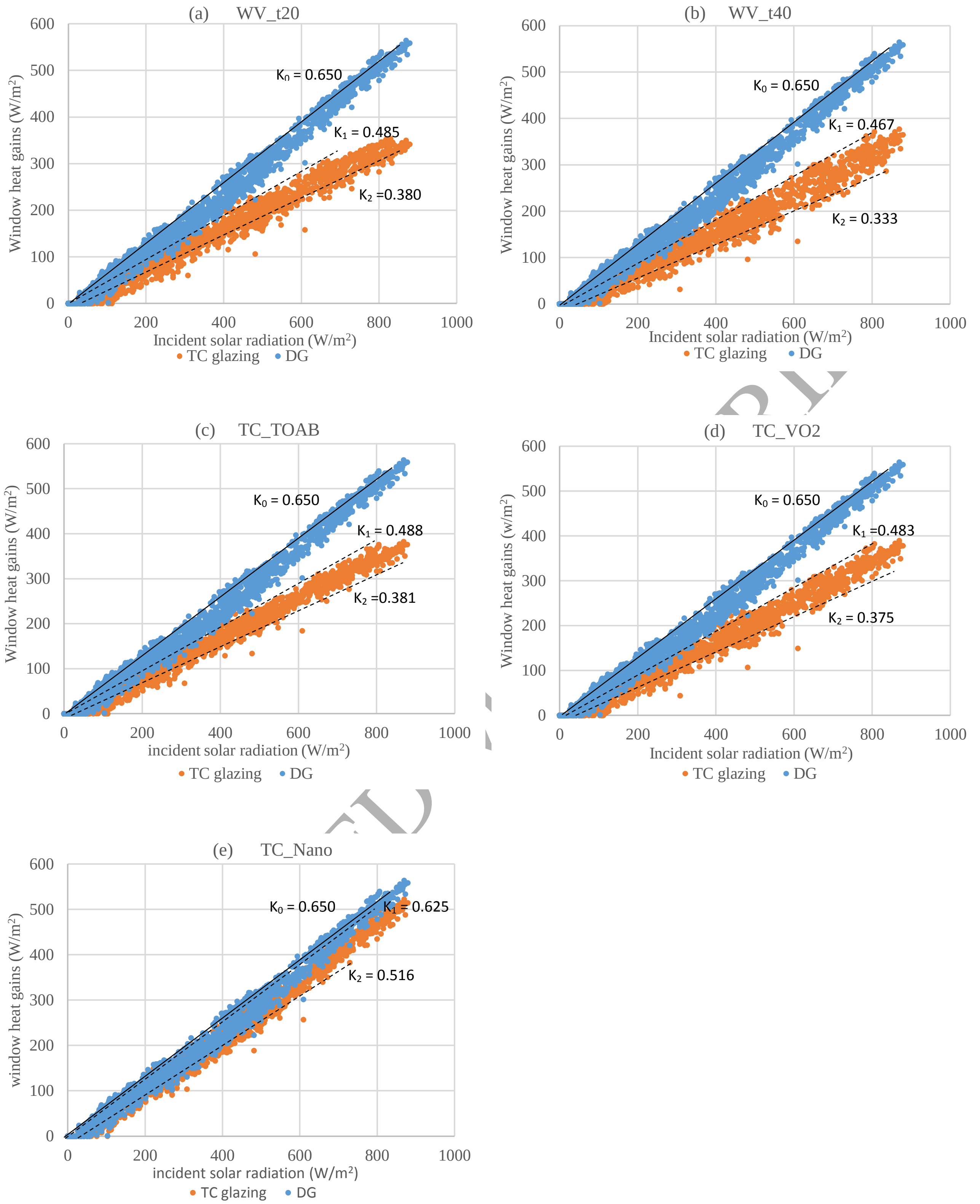



**Figure 7: Solar Heat Gain Coefficient (SHGC) of standard double glazing and five studied TC windows annually in Beijing,**

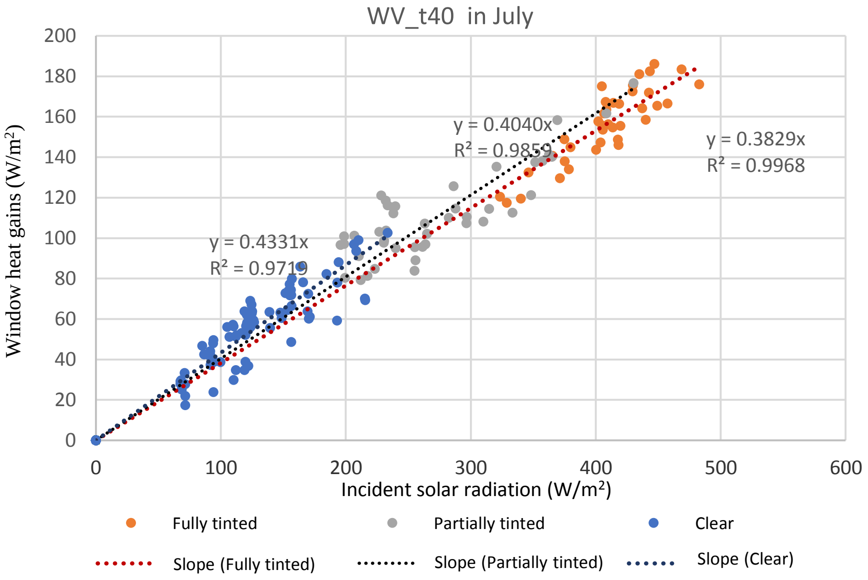



**Figure 8: the detailed SHGC changing with three states of WV_t40 in the hottest month of July.**

The values of SHGC only show the capability of TC windows for transferring incident solar radiation to window heat gains annually. However, window heat gain can be either beneficial or detrimental to the heat balance and energy consumption of the building. The ideal thermochromic window would limit solar heat gains when the thermal zone is in cooling mode and admit solar heat gains when the zone is in heating mode. Figure 9 shows the window heat gains caused by all studied TC windows and reference double glazing during the heating period (Nov to Apr) and cooling period (May to Oct) respectively under the climatic conditions of Beijing. As can be seen, total window heat gains of all windows during the heating period are higher than that of the cooling period, caused by a larger transmitted solar radiation during winter. This is because solar altitude increases in summer, resulting in less solar radiation falling on the vertical surface of a building (as shown in Figure 2). As aforementioned, window heat gains mainly consist of transmitted solar radiation (yellow column) and secondary heat gain (orange column) shown in Figure 9 (b). For all of the TC windows, excluding $NVO_2$_t40, it is noted that secondary solar heat gains account for a large proportion of window heat gain, ranging from 32.89% to 42.89%, during the cooling period. This, in turn, means reducing solar transmittance is not the only way to reduce cooling load in summer, lower secondary heat gain can potentially also reduce window solar heat gain. As mentioned in section 3.1.1, lower solar absorptance results in lower window temperature, which decreases the temperature difference between window surface and indoor temperature and hence reduces convection between the window and room space. Meanwhile, lower emissivity can reduce the long-wave radiation heat flow to the room from the indoor glass surface. Lower solar absorptance and emissivity both yield lower secondary heat gains. $VO_2$_t38 shows the lowest secondary heat gain of 68.37 W/m$^2$ than the other four types of TC windows (i.e. secondary heat gain ranging across 69.88-97.21 W/m$^2$) produced during the cooling period. This is the combined action of its relatively low solar absorptance (0.31-0.41) and emissivity ( 0.83-0.97), as shown in Table 2. Meanwhile, the lower secondary heat gains of $VO_2$_t38 reverse the disadvantage of the higher transmitted solar radiation. Therefore, in terms of window heat gains, higher solar absorptance and emissivity may not be the desirable properties for TC windows in summer.

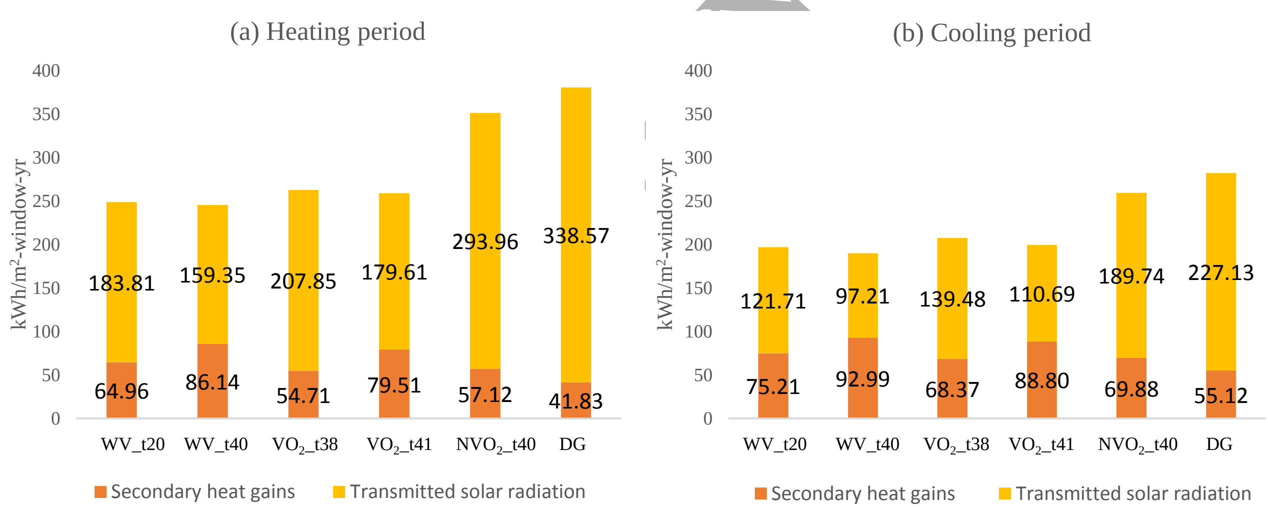
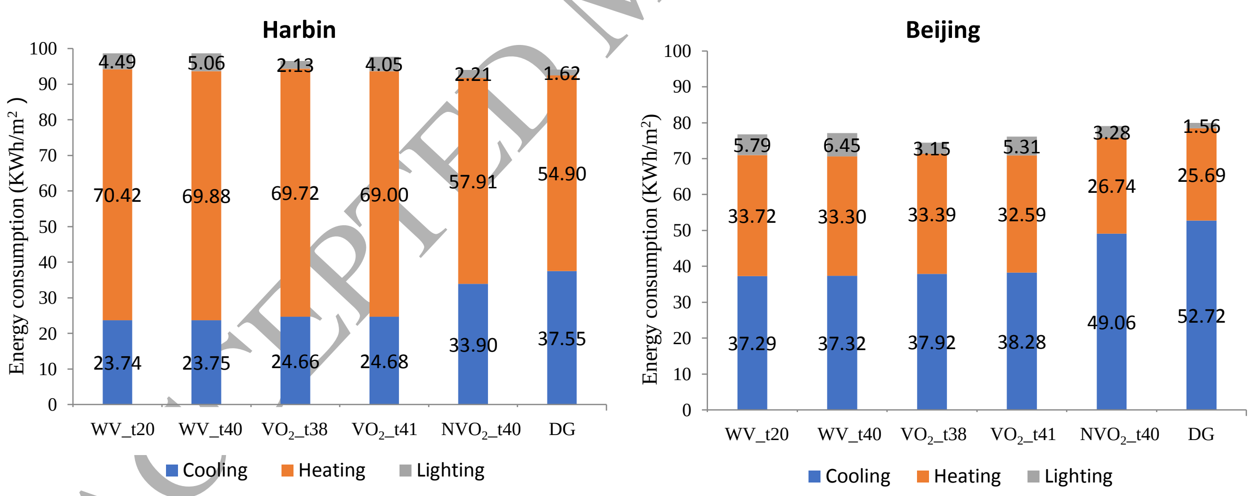



**Figure 9: Breakdowns of window heat gains in heating and cooling periods respectively**

## 3.2. Overall total energy consumption under five different climates in China

To explore the effect of TC window on building energy performance, the total energy consumption of the office was predicted under five different climates in China, and the results can be found in Figure 10. Under all of the tested climatic conditions but Harbin, the TC windows result in energy saving up to 19.9% when compared with traditional clear double glazing. TC windows reduced cooling consumption, whilst increasing heating and lighting consumption simultaneously. However, the presence of any TC glazing gave rise to the overall higher energy consumption in Harbin, since the increase of heating and lighting demand countered the decrease of energy consumption caused by cooling reduction. This is due to the fact that Harbin has a longer heating season and the outdoor temperature is extremely low (i.e. the average outdoor temperature in winter is - 20°C). Thus, 58% of the annual energy consumption is caused by heating for a room with traditional clear double glazing, whilst for the other four climates, heating consumption accounted for only up to 30%. The reduced solar transmittance of TC glazing in both S-state and M-state obstructs more solar heat gains for passive heating during the heating season, indicating that TC glazing might not be suitable to be applied in severely cold climates.

It can also be seen that the reduced cooling energy and increased heating energy caused by WV_t20, WV_t40, $VO_2$_t38 and $VO_2$_t41are similar under five climatic conditions, although they have different transition temperatures and optical properties (see Table 2). For example, under Beijing's climate, cooling energy is reduced by between 27.39 and 29.27% (i.e. 1.88% difference between these four types of TC windows) and heating energy is increased by between 26.86 and 31.26% (i.e. 4.4% difference) when compared with clear double glazing. $VO_2$_t38 showed the lowest energy consumption amongst the four types of TC glazing. Overall, energy saving caused by $VO_2$_t38 was 6.9% in Beijing, 9.12% in Hangzhou, 19.9% in Kunming and 13% in Guangzhou. As can be seen, $VO_2$_t38 has less impact on lighting energy consumption because of its relatively high visible transmittance (51% at M-state, 61% at S-state). Among these four types of thermochromic glazing, WV_t20 has a relatively low transition temperature of 20°C and therefore, as expected, its tinted state is easier to achieve than for the other three TCs under the same climatic conditions. This would result in increased tinted hours for WV_t20 to block solar heat from being transmitted inside. However, it did not show significant benefit for energy performance over the other three. It is mostly due to the restricted modulation of solar transmittance, which changes from 44% to 39% with temperature raising over transition temperature. Therefore, there is neither significant reduction of cooling energy on hot days nor a large increase of heating consumption on cold days. WV_t40, $VO_2$_t38, and $VO_2$_t41 have a relatively larger solar transmittance reduction of 12.4%, 8.0% and 10.5% respectively. Although their tinted states are more difficult to achieve because of the higher transition temperatures (of around 40°C) required, their heating and cooling energy consumptions are similar to that of WV_t20. This means that a higher transition temperature, which is an undesirable feature for TC materials, could be overcome by enlarging solar transmittance modulation. $NVO_2$_t40 results in the least energy conservation of all five TCs, ranging across 0.15%-3.02% in Beijing, Hangzhou, Kunming, and Guangzhou, when compared with clear double glazing. The reason behind the undesirable performance of $NVO_2$_t40 is that its solar transmittance at S-state before tinting is 69%, which is quite close to that of double glazing (78%), and its solar transmittance is 57% at M-state after tinting, which is even higher than the transmittance of the other four TC windows before tinting (i.e. 46% maximum). This means it did not provide sufficient reduction for the penetration of solar energy during hot days.



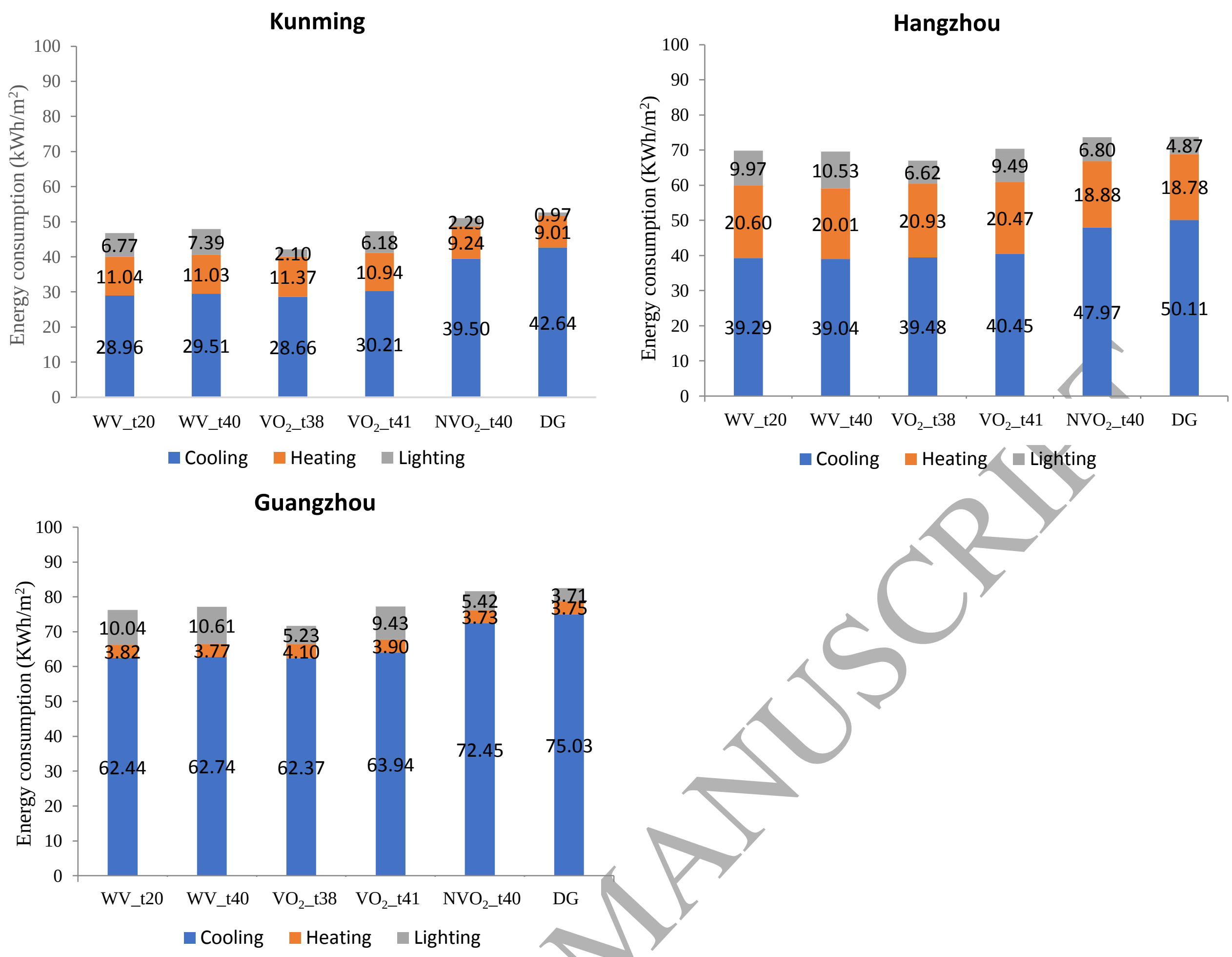



**Figure 10: Total energy consumption of room with WWR of 60%, including heating, cooling and lighting, classified by different climatic conditions WV_t20 (Tt=20°C, $T_{sol}$ 0.440 -0.390) WV_t40 (Tt=40°C, $T_{sol}$ 0.412 -0.39); $VO_2$_t38 (Tt=38.5°C, $T_{sol}$ 0.460 -0.380); $VO_2$_t41 (Tt=41.3°C, $T_{sol}$ 0.44 -0.355); $NVO_2$_t40 (Tt=40°C, $T_{sol}$ 0.69 -0.57**

### 3.3. The effects of thermochromic glazing on indoor daylight performance and lighting demand

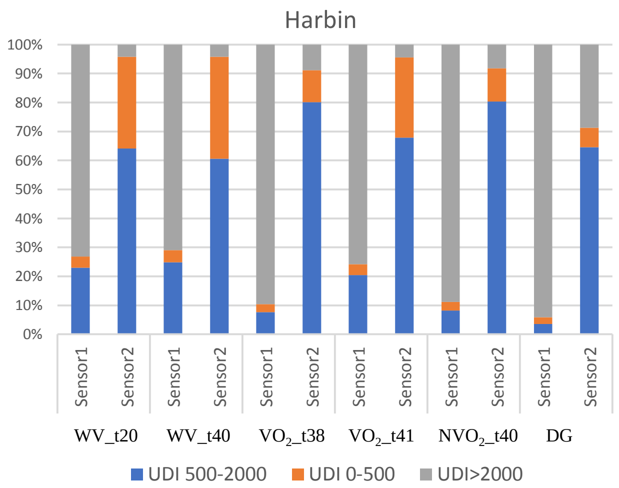
Useful daylight illuminance (UDI) was used to evaluate daylight performance for reference double glazing (DG) and TC windows under five different climatic conditions. Figure 11 shows the predicted UDI at sensors 1 and 2 during working period, respectively. The orange, blue and grey columns represent $UDI_{0\text{-}500lux}$, $UDI_{500\text{-}2000lux}$, and $UDI_{>2000lux}$, respectively. When the illuminance is lower than 500 lux, artificial lighting is required to supplement visual comfort in the office, which means extra lighting energy will be consumed. It can be seen that the working hours falling into the undersupply $UDI_{0\text{-}500lux}$ bins of both sensor 1 and sensor 2 are increased by TC windows under all climates when compared to the use of traditional double glazing. This is because the visible transmittances of all the studied TC windows are lower than that of the traditional clear double glazing, indicating that less daylighting transmits through the windows. Oversupplied illuminance (over 2000lux) on the work plane might cause glare or overheating problems. Therefore, the values of $UDI_{>2000lux}$ should also be investigated. The simulation results present that all studied TC windows reduce the percentage of oversupply daylight hours ($UDI_{>2000lux}$) when compared with DG under all climatic conditions. Upon the dual effect of increasing undersupply daylight hours ($UDI_{0\text{-}500lux}$) and decreasing oversupply daylight hours ($UDI_{>2000lux}$) caused by the studied TC windows, the percentage of hours where UDI is in the most desired range might increase or decrease when compared with DG under different climatic conditions. This has been investigated in this section. For office buildings, the desired range of illumination is from 500 lux to 2000 lux [46], where sufficient daylight without compensation from artificial lighting for working is available, meanwhile avoiding visual discomfort caused by oversupply daylighting. Figure 11 illustrates the annual percentage of each UDI bin for the selected glazing under the five climatic conditions.

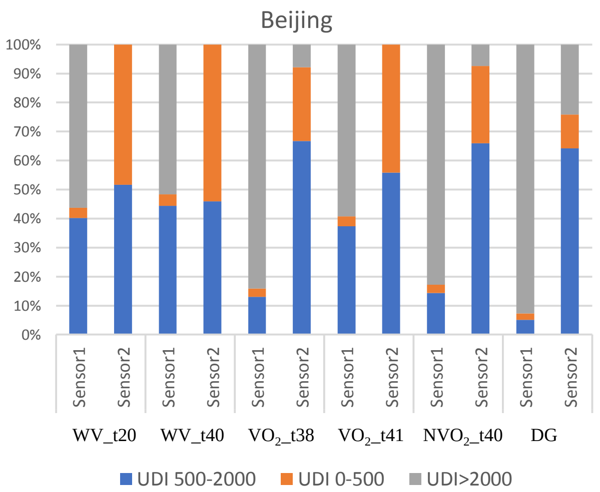
Depending on the optical properties, the five types of TC windows were classified into two groups: The first group includes WV_t20, WV_t40, and $VO_2$_t41, which have relatively low visible transmittances of around 40% (Low VT group) and the other group consists of $VO_2$_t38 and $NVO_2$_t40, which have relatively higher visible transmittances of approximately 60% (High VT group). For the selected traditional DG, $UDI_{>2000lux}$ dominates for sensor 1, and $UDI_{500\text{-}2000lux}$ accounts for a large proportion at sensor 2 (i.e. 57.81-76.94%) under all climates. This means that oversupply of daylight is the main issue for the region close to the window. For the low VT group, the working hours within the most desired range of UDI ($UDI_{500\text{-}2000lux}$) increase at sensor 1, whilst decreasing at sensor 2 when compared to that of the selected traditional glazing. Taking Beijing as an example, comparing with the reference DG, the values of $UDI_{500\text{-}2000lux}$ at sensor 1 increased by 35.08%, 39.33% and 32.21% respectively, which is dominantly caused by decreasing hours of oversupply daylighting ($UDI_{>2000lux}$). At sensor 2, the working hours falling into the desired $UDI_{500\text{-}2000lux}$ bin are reduced under the effect of these three TC windows by 12.55%, 18.23%, and 8.4%, mostly caused by increasing percentages of undersupplied daylight hours ($UDI_{0-500lux}$), which increase from 11.71% to 48.37%, 54.05%, and 44.22% respectively. For the high VT group, the desired daylight hours (i.e. hours in $UDI_{500-2000lux}$ bin) at both sensor 1 and sensor 2 are higher than DG. However, the increasing range at sensor 1 was 7.95% and 9.24% respectively, which is less significant than that caused by TC window in the low VT group. For sensor 2, the percentages of desired daylight ($UDI_{500-2000lux}$) increase by 2.52% and 1.83% respectively when compared with DG. This is because the increase of undersupplied daylighting hours ($UDI_{0-500lux}$) cannot reverse the upward trend of the working hours falling in the most desired daylight range ($UDI_{500-2000lux}$).

Under different climates, the distribution of UDI bins for the five TC windows changes dramatically. In the following discussion, WV_t40 is chosen as an example of the low VT group, and VO2_t38 is selected as a representative of the high VT group. For the room with WV_t40 applied, working hours falling in the desired daylight range ($UDI_{500-2000lux}$) at sensor 2 are more than that of sensor 1 under the climatic conditions of Harbin and Beijing, while in Kunming, Hangzhou, and Guangzhou, sensor 1 reversely has more hours within the most desired $UDI_{500-2000lux}$ bin. Additionally, when compared with DG, WV_t40 induced a significant reduction of desired daylight hours ($UDI_{500-2000lux}$) at sensor 2 with the decrease of latitude geographically. This is likely a consequence of the relationship between solar altitude and the depth that daylight can access, which means that it is more difficult for direct solar radiation to reach the working plane in the region far away from the window when solar altitude is high. Therefore, a TC window with low visible transmittance blocks more accessible daylighting and aggravates this issue. For $VO_2$_t38, the percentage of working hours within desired daylighting range ($UDI_{500-2000lux}$) of sensor 1 is lower than that of sensor 2 under all climates. At sensor 1, the desired daylight hours ($UDI_{500-2000lux}$) are more than that of DG. For the region of sensor 2, when compared with DG, the percentage of $UDI_{500-2000lux}$ is increased by up to 15.52% in Harbin, Beijing, and Kunming, but slightly reduced by 5.04% and 1.04% respectively in Hangzhou and Guangzhou. This is also due to the relationship between solar altitude and the depth of daylighting to access, in addition to the fact that a higher solar altitude slightly reverses the upward trend of $UDI_{500\text{-}2000lux}$ at sensor 2. In conclusion, the TC windows with the higher visible transmittances could be relatively less influenced by different climates in terms of desirable daylighting availability.

To sum up, because of lower visible transmittance than standard double glazing, the TC glazing has a feature of reducing visual discomfort caused by excessive daylighting. The TC windows with relatively lower visible transmittance, including WV_t20, WV_t40, and $NVO_2$_t40, significantly improved the visual comfort levels of the region near the window (sensor 1) under all climatic conditions. However, in the region far away from the window (sensor 2), daylighting levels are linked to climatic conditions, particularly to climates with low latitude such as Hangzhou and Guangzhou, which would result in increasing the percentage of working hours within the undersupplied daylight range ($UDI_{0\text{-}500lux}$), and hence consuming extra lighting energy. The TC windows with relatively higher visible transmittances, including $VO_2$_t38 and $NVO_2$_t40, also improved visual comfort levels of the whole room under the climatic conditions of Harbin, Beijing, and Kunming. The influence of higher solar altitude in Hangzhou and Shanghai has not led to significant decrease of desired daylighting hours ($UDI_{500\text{-}2000lux}$) compared with DG. This indicates that the TC windows with higher visible transmittance are more flexible to be applied under various climates from the perspective of daylight comfort.





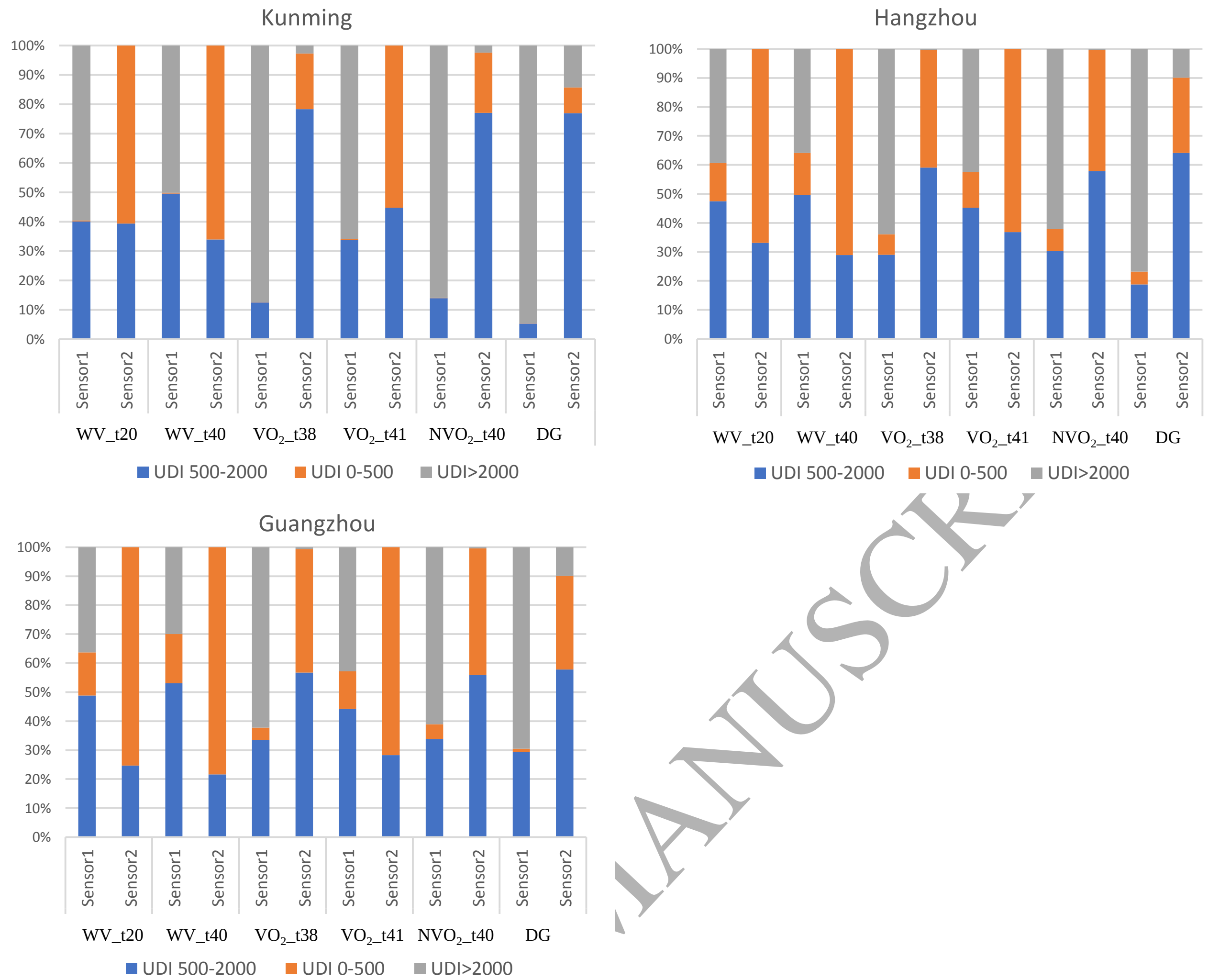



**Figure 11: Annual percentage of UDI$_{0\text{-}500lux}$, UDI$_{500\text{-}2000lux}$ and UDI$_{>2000lux}$ levels of illuminance sensors 1 and 2 in an office room with five types of TC windows and reference DG applied respectively under five climatic conditions.**

### 3.4. Effects of WWR on TC performance energy and visual comfort

In order to explore the appropriate window size for using TC windows under different climatic conditions, the simulations were conducted under ten scenarios with different window-to-wall ratios (WWRs), which ranged from 0.1 to 1 at the intervals of 0.1. The building energy consumption and annual percentage of UDI$_{500\text{-}2000lux}$ for the selected TC windows and DG window at different WWRs under Beijing's climatic condition are illustrated in Figure 12. Energy consumption changing with WWRs is shown in stacked bars for cooling (grey), heating (yellow), and artificial lighting energy (blue). The two curves show the values of UDI$_{500\text{-}2000lux}$ that vary with WWRs in the region close to (sensor 1) and far away (sensor 2) from the window. It must be noted that the results of this study are valid for a room with the described conditions and dimensions, with a single opening placed in the south-facing surface.

Regarding standard double glazing (DG), cooling energy consumption was found to increase with the increasing of window size (i.e. WWR increasing from 0.1 to 1) and becomes the dominant energy consumer. Additionally, the percentage of working hours within the desired daylight range ($UDI_{500\text{-}2000lux}$) at sensor 1 is reduced, because of more oversupplied daylight hours (>2000lux), whereas arbitrarily reducing the WWRs results in the increase of heating energy consumption and extra artificial lighting to supplement the undersupplied daylighting (<500lux). Under the same window size, the pairwise comparison between each type of TC window and the reference DG with respect to total energy consumption indicates that TC windows can only provide energy conservation for large window sizes, where cooling energy consumption is dominant. In order to specify the window size when energy saving could be achieved, the corresponding range of WWRs is proposed and named as energy saving range (labelled as ES). For the daylight performance, as can be seen, there is a trade-off relationship between the values of $UDI_{500\text{-}2000lux}$ at sensor 1 and sensor 2. At the cross point of the two curves, the same percentage of working hours fall into desired daylight range for both sensors. This means oversupplied daylighting in the region close to the window caused by larger windows and undersupplied daylighting in the region far away from the window caused by smaller windows are mostly avoided. The corresponding WWR of the cross point at x-axis is defined as WWR for balanced illuminance (labelled as BI). For a particular TC window, if the WWR for balanced illuminance (BI) is in the energy-saving range (ES), both energy conservation and visual comfort can be achieved simultaneously.

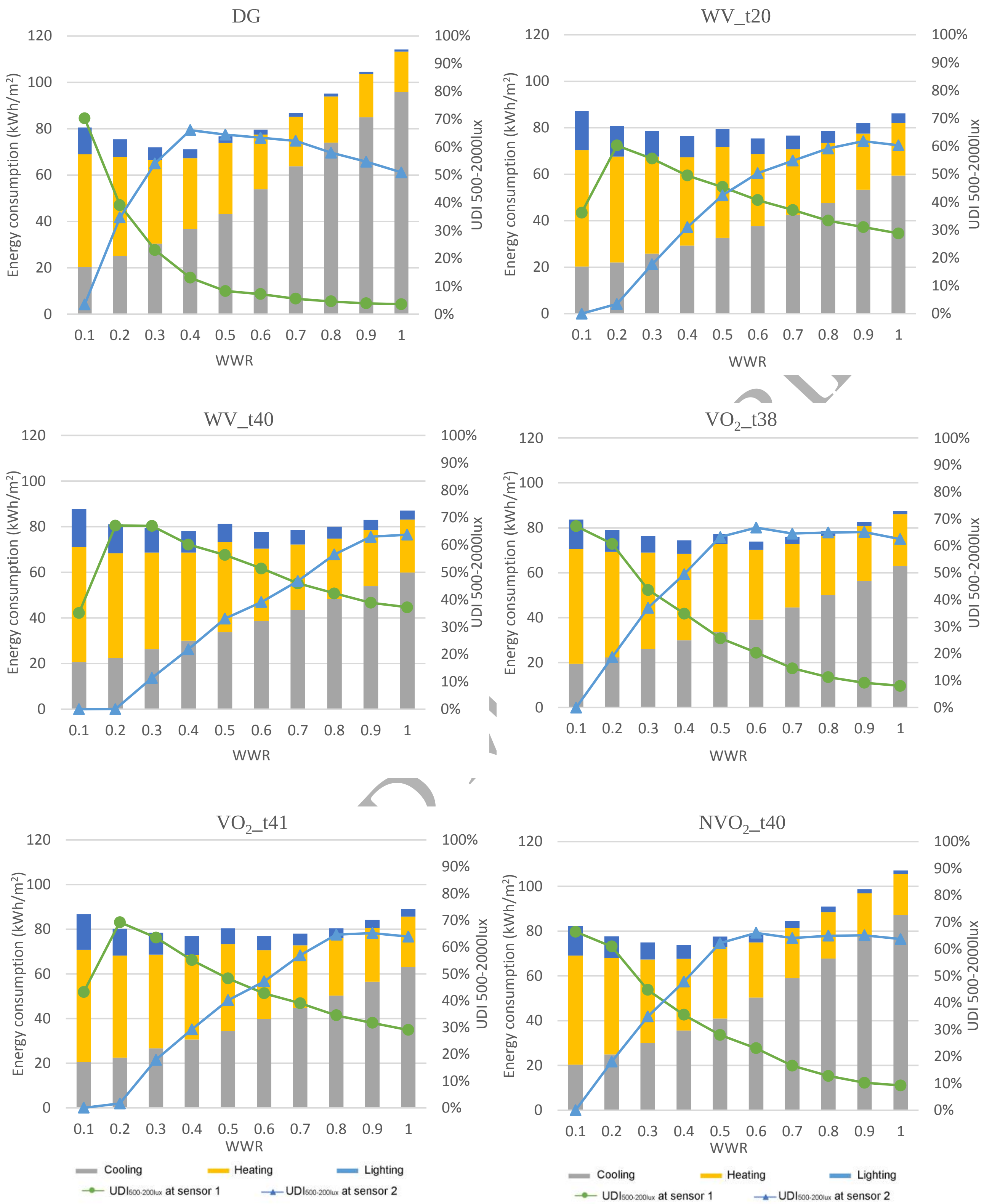



**Figure 12: Building energy consumption and daylight performance for various TC windows at the different window to wall rations under Beijing's climatic condition**

As can be seen in Figure 12, all of the studied TC windows apart from $NVO_2$_t40 have a similar tendency of energy consumption changing with varying window size. Taking WV_t40 as an example, When the WWR is between 0.6 and 1 (i.e. ES is also 0.6-1 for WV_t40) under the climatic conditions of Beijing, WV_t40 causes a decrease of total energy consumption ranging from 2.42% to 23.75% when compared with reference DG; Increasing window size can result in more energy conservation. The remaining four TC windows also have a similar energy saving range of 0.6-1. However, the decrease of energy consumption from applying $NVO_2$_t40 is less significant than the other TCs when compared with DG, which is up to 6.17%. This is consistent with the discussion conducted in section 3.2. In terms of balanced illuminance, DG shows a cross point of $UDI_{500\text{-}2000lux}$ curves of sensor 1 and sensor 2 when the WWR is 0.2 (i.e. BI value is 0.2 for DG) under the climatic conditions of Beijing and the corresponding desired daylight hours account for 37% of working hours (i.e. $UDI_{500\text{-}2000lux}$ for sensor 1 = $UDI_{500\text{-}2000lux}$ for sensor 2 = 37%). This means a small window size is more desirable for clear double glazing as the issue of oversupplied daylighting can be moderated. Compared with DG, all the TC windows achieve higher BI values. This can be explained by the fact that the TC windows diminish oversupplied daylighting and increase $UDI_{500\text{-}2000lux}$. For WV_t40, the balanced illuminance occurs when WWR is 0.7, and it has fallen into its energy saving range of 0.6 -1, which means that a WWR of around 0.7 is the desired window size for using WV_t40 windows in Beijing, in terms of energy saving and daylight performance improvement. For WV_t20, and $NVO_2$_t40, BI values were found to be 0.5 and 0.6 respectively, with a balanced $UDI_{500\text{-}2000lux}$ of around 46%. $VO_2$_t38 and $NVO_2$_t40 have lower BI values than the others of 0.3 and 0.4 respectively. The $UDI_{500\text{-}2000lux}$ values of their cross points are 40.69% and 40.14% respectively.

**Table 3. Summarised Energy Saving range (ES) and Balanced Illuminance (BI) under the suitable window to wall ratios for five types of TC glazing and reference DG under the five selected climates respectively**

| | **Harbin** | | **Beijing** | | **Hangzhou** | | **Kunming** | | **Guangzhou** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ES | BI | ES | BI | ES | BI | ES | BI | ES | BI |
| **WV_t20** | 0.8-1 | 0.5 | 0.6-1 | 0.5 | 0.5-1 | 0.7 | 0.5-1 | 0.6 | 0.3-1 | 0.6 |
| **WV_t40** | 0.8-1 | 0.5 | 0.6-1 | 0.7 | 0.6-1 | 0.9 | 0.6-1 | 0.8 | 0.3-1 | 1 |
| **$VO_2$_t38** | 0.7-1 | 0.3 | 0.6-1 | 0.4 | 0.4-1 | 0.5 | 0.3-1 | 0.4 | 0.3-1 | 0.5 |
| **$VO_2$_t41** | 0.7-1 | 0.4 | 0.6-1 | 0.6 | 0.6-1 | 0.8 | 0.6-1 | 0.7 | 0.3-1 | 0.8 |
| **$NVO_2$_t40** | 0.6-1 | 0.3 | 0.6-1 | 0.4 | 0.6-1 | 0.5 | 0.6-1 | 0.4 | 0.6-1 | 0.6 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **DG** | — | 0.2 | — | 0.2 | — | 0.3 | | 0.2 | — | 0.4 |

Table 3 specifies the ES and BI values of five TC windows under the studied climatic conditions. As can be seen, with increasing latitudes, the ES range of all TC windows (excluding $NVO_2$_t40) broadens, with the maximum increase being from 0.3-1 to 0.8-1. This means that in the climates with a cold winter, a larger window area is required to receive more solar heat gains on cold days to make up the reduction in transmitted solar radiation caused by the TC windows. Meanwhile, BIs of all TC windows are seen to increase with a decrease in latitude, which means higher solar altitudes increase the difficulty for daylight to reach the region far away from the window. Thus a larger window size is necessary to improve daylight distribution. In addition, it can be seen that the TC windows with lower visible transmittance are more sensitive to the altitude changing, e.g. WV_t40 results in an increase of BI values ranging from 0.5 to 1 with the increase in solar altitudes. However, for $VO_2$_t38, which has a relatively higher visible transmittance, it changes slightly from 0.3 to 0.5. Under the climatic conditions of Harbin, there are no BI values falling into the ES range, which means that simultaneously achieving both energy saving and desired daylight availability is difficult. On the contrary, in Guangzhou, the BIs of all studied TC windows are within their corresponding energy saving ranges respectively, which means that every TC window has the potential to attain energy efficient and desirable daylight availability at the same time by using an appropriate window size. For Hangzhou and Kunming, all TCs except $NVO_2$_t40 has a BI which falls within the range of ES. For Beijing, only limited types of TC windows (i.e. WV_t40 and $NVO_2$_t40) have this appropriate window size. This indicates that TC windows are more flexible to be used under climatic conditions with lower latitudes, which have more cooling demand.

## 4. Conclusions

$VO_2$-based thermochromic materials have potential to improve both building energy performance and visual comfort compared with standard double glazing. This research developed a comprehensive analytical method for five types of well-developed thermochromic windows with different transition temperatures and optical properties under five representative climatic conditions in China. Based on a building simulation for a typical office room in EnergyPlus, the thermal and optical behaviours of all the studied TC windows and their influence on building energy consumption and daylight performance was investigated. The following conclusions can be drawn:

1) Lowering transition temperature is not an essential requirement for applying TC windows to buildings, which may bring undesirable tinted hours on cold days leading to increased heating energy consumption. Enlarging the change of solar transmittance has the potential to be relatively more efficient in attaining desirable thermochromic performance.
2) The TC layer temperature depends on the combined effect of the solar absorptance of the window alongside ambient conditions (including ambient temperature and incident solar radiation intensity). TC windows with relatively lower absorptance and higher transition temperatures, such as $VO_2$_t38 and $NVO_2$_t40, required higher ambient temperature and solar radiation to trigger the transition.
3) The thermochromic glazing mainly provides energy saving by reducing the cooling demand of the building. Thus, the severe cold zone in China, where heating consumption dominates, would not be an appropriate climatic condition to use TC windows. All five types of thermochromic glazing, excluding $NVO_2$_t40, have similar heating and cooling energy performances, however, the lower lighting energy consumption of $VO_2$_t38 results in the most significant energy conservation when compared with clear double glazing.
4) For daylighting availability, all types of thermochromic glazing were shown to lead to an increase in desired annual daylight hours within $UDI_{500\text{-}2000lux}$, in the region near the window (sensor 1). In the region far away from the window (sensor 2), the desired $UDI_{500\text{-}2000lux}$ is significantly reduced by TC windows due to lower visible transmittances, and this reduction increases with the increase of solar altitudes.

5) Considering the appropriate window-to-wall ratio for using a particular thermochromic window, results show that under the climatic conditions of Hangzhou, Kunming and Guangzhou, most types of thermochromic glazing had the potential to achieve both energy saving and desired daylighting simultaneously. However, there are limited types of thermochromic glazing which could also achieve both energy saving and desired daylighting under colder climates, such as that of Beijing and Harbin.

This study has investigated the building energy performance and daylight availability affected by different types of TC windows under different climatic conditions, with results valid for the room with specified conditions and dimensions. The material properties (i.e. transition temperature, absorptance, modulation of solar transmittance) that would influence the performance of using TC windows have been briefly discussed, however, further research about their particular influence will be conducted in future studies.

## Conflicts of Interest Statement

Runqi Liang, Yanyi Sun, Marina Aburas, Robin Wilson and Yupeng Wu declare that they have no conflict of interest

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